Chapter 2

AgMIP's Transdisciplinary Agricultural Systems Approach to Regional Integrated Assessment of Climate Impacts, Vulnerability, and Adaptation

John M. Antle[1], Roberto O. Valdivia[1], Kenneth J. Boote[2], Sander Janssen[3], James W. Jones[2], Cheryl H. Porter[2], Cynthia Rosenzweig[4,5], Alexander C. Ruane[4], and Peter J. Thorburn[6]

[1]*Oregon State University, Corvallis, OR, USA*

[2]*University of Florida, Gainesville, FL, USA*

[3]*Wageningen University, Wageningen, the Netherlands*

[4]*NASA Goddard Institute for Space Studies, New York, NY, USA*

[5]*Columbia University, New York, NY, USA*

[6]*Commonwealth Scientific and Industrial Research Organization, Brisbane, Australia*

Introduction

This chapter describes methods developed by the Agricultural Model Intercomparison and Improvement Project (AgMIP) to implement a transdisciplinary, systems-based approach for regional-scale (local to national) integrated assessment of agricultural systems under future climate, biophysical, and socio-economic conditions. These methods were used by the AgMIP regional research teams in Sub-Saharan Africa and South Asia to implement the analyses reported in their respective chapters of this book. Additional technical details for these methods are provided in Appendix 1: *Guide for Regional Integrated Assessments: Handbook of Methods and Procedures*, which is also available on the AgMIP website at http://agmip.org.

The principal goal that motivates AgMIP's regional integrated assessment (RIA) methodology is to provide scientifically rigorous information needed to support improved decision-making by various stakeholders, ranging from local to national and international non-governmental and governmental organizations. To meet this goal, through interactions with stakeholders and researchers, a number of key features of the approach were identified:

- A protocol approach must be used that is based on a rigorously documented methodology so that results can be replicated and intercompared, and so that methods can be improved over time.
- The study design must be made with input from stakeholders and policymakers, and include the systems and adaptations to be investigated, the future pathways and scenarios to be used in the assessments, and the identification of impact indicators to be used.
- A transdisciplinary, systems-based approach is needed that can incorporate important features of current and possible future systems, including multiple crops, inter-crops, livestock, and non-agricultural sources of income. The approach must provide a sufficient multi-climate level of detail about the production systems to allow meaningful characterization of possible adaptations.
- The approach must be able to account for the highly diverse types of systems, and the widely varying biophysical and socio-economic conditions that characterize farms.
- The approach must be able to incorporate the high degree of heterogeneity in biophysical and economic conditions typical of most agricultural regions.
- The methods must be able to quantify vulnerability to climate change in a meaningful way, i.e., it must be possible to characterize the impacts on those farm households that are adversely affected by climate change, as well as those that benefit from climate change. In other words, it must be possible to quantify not only average impacts but also the distribution of impacts in diverse populations.
- Key uncertainties in climate, crop, biophysical, and economic dimensions of the analysis must be assessed and reported so that decision-makers can understand them and use them to interpret the results of the analysis (see Part1, Chapters 9 and 10 in this volume).

Key Indicators and Core Climate Impact Questions

Based on discussions with stakeholders as well as the large body of research on climate change and its impacts, a number of key indicators were identified to assess impact, vulnerability, and adaptation, that are consistent with the key features

presented above:

- Changes in climate (temperature, precipitation, and carbon dioxide concentrations).
- Changes in average (or aggregate) physical production for principal production activities of the system, a key factor in regional and local food security.
- The proportion of households that are adversely affected by climate change through changes in the productivity of their agricultural system; a measure of the degree of vulnerability to climate change.
- The proportion of households that may benefit from climate change through changes in the productivity of their agricultural system; a measure of the size of the non-vulnerable population.
- Changes in average monetary value of the production system's outputs (an aggregate measure of the system's productivity) for losers and gainers, to indicate the magnitude of vulnerability as well as potential positive impacts.
- Average household *per capita* income; a measure of overall well-being, closely related to household food security.
- The headcount poverty rate in the population (i.e., the proportion of households below the poverty line); another key indicator of economic well-being for both vulnerable and non-vulnerable segments of the population.

The RIA methodology is designed to quantify the impacts of climate change on agricultural systems by using the above indicators. AgMIP has identified the following core research questions that allow the above indicators to be quantified in ways that support informed decision-making by various stakeholders (see Fig. 1):

Question 1. What is the sensitivity of current agricultural production systems to climate change? This question addresses the impacts of climate changes, assuming that the production system does not change from its current state under current biophysical and socio-economic conditions. While this type of analysis can provide some insights into potential impacts, its relevance is limited because of the use of current socio-economic conditions to quantify impacts.

Question 2. What is the impact of climate change on future agricultural production systems? This question evaluates the impacts of climate change on the production system that is projected for a future world without climate change. In contrast to the analysis done for Question 1, the analysis is carried out under biophysical and socio-economic conditions projected into the future with and without climate changes. This type of analysis is more relevant to understanding climate impacts and thus the potential benefits of adaptation, but is more challenging because all of the relevant variables affecting the systems must be projected into the future.

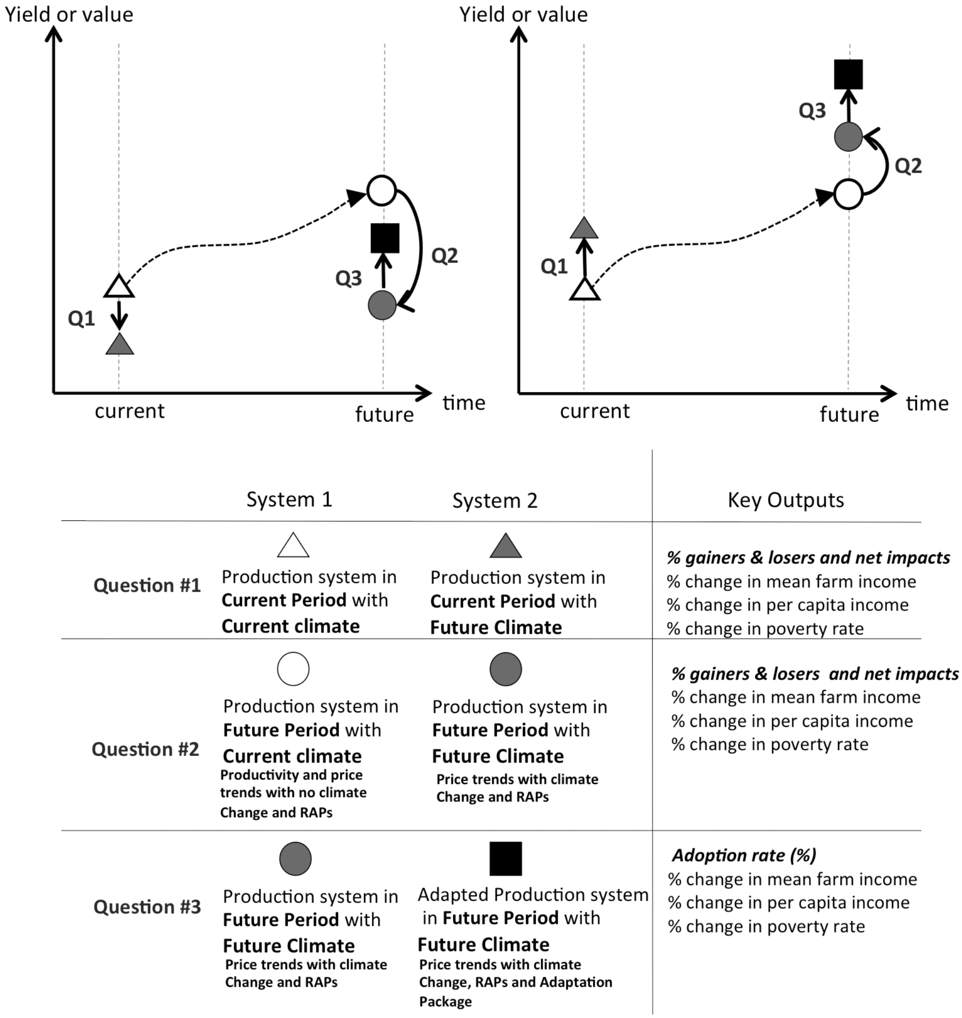

Fig. 1. The three core questions for the case of negative (top, left) and positive (top, right) climate impacts.

Question 3. What are the benefits of climate change adaptations? This question addresses the design of adaptation options for the future production systems, the degree to which they would be likely to be adopted, and the economic, environmental, and social outcomes that would be associated with their use. These adaptations are designed to offset the adverse impacts of climate change (Fig. 1, left) or take better advantage of positive impacts (Fig. 1, right).

It is also worth noting that an analysis of adaptation (Question 3) can also be done under current climate, biophysical, and socio-economic conditions, and this

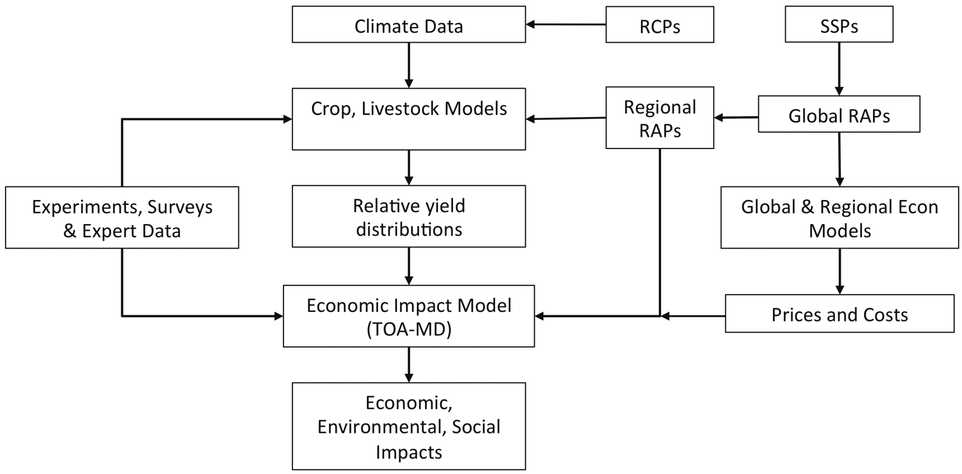

Fig. 2. The AgMIP RIA framework. RCP = representative concentration pathway. SSP = shared socio-economic pathway. RAP = representative agricultural pathway. TOA-MD = Tradeoff Analysis Model for Multi-dimensional Impact Assessment.

would be equivalent to a multi-dimensional impact assessment of a technology as described by Antle (2011).

The AgMIP Regional Integrated Assessment Framework

To implement analysis that could address these three core questions, AgMIP developed an integrated assessment framework for both global and regional analysis (Fig. 2). As in earlier modeling studies, this framework combines climate and biophysical data and models with economic data and models. However, there are several notable features of this framework that represent methodological advances.

A protocol-based approach

One of the major limitations of most previous studies of climate impacts and adaptation is that many different methods for designing scenarios and implementing models are used, and the details of the methods used are not well documented. A major contribution of the AgMIP approach is that it is based on well-defined protocols (as described in detail in the *AgMIP RIA Handbook*, Part 1, Appendix 1 in this volume). These protocols cover all of the components in Fig. 2: the downscaling of climate data (e.g., from the Coupled Model Intercomparison Project, CMIP5); (Taylor *et al.*, 2009), the parameterization and use of crop and livestock simulation models; the creation of pathways and scenarios to project the analysis into the future; and the parameterization and use of economic data and models.

Data and model linkage through new IT tools

A critical component in the implementation of the protocol-based approach is a systematic way to manage both input and output data of the various models. AgMIP has developed a set of new tools to do this, described in Part 1, Chapter 6 in this volume.

Concentration pathways and climate models

The models are implemented for multiple greenhouse-gas concentration pathways (representative concentration pathways, or RCPs; Moss *et al.*, 2010), using the more recent CMIP5 data, downscaled to the scale at which the crop and livestock models are implemented (see Part 1, Chapter 3 in this volume for further details). Data from multiple climate models can be used to represent uncertainty in climate projections.

Future development pathways

To characterize future non-climate biophysical conditions and socio-economic conditions, global shared socio-economic pathways (SSPs) are combined with global and regional representative agricultural pathways (RAPs; see Part 1, Chapter 5 in this volume) and data from global economic models to characterize future conditions at the regional and farm level relevant to the analysis of impact and adaptation, as discussed in Chapter 5 in detail. In principle, various SSPs and RAPs can be incorporated into an analysis to represent alternative possible future conditions, and to represent uncertainty about the future.

Impacts of climate change and adaptation on system productivity

Crop and livestock models are simulated on a site-specific basis to characterize the impacts of climate change on the distribution of relative yields (i.e., the yield under future climate conditions relative to the yield under current climate conditions) in the farm population (see Part 1, Chapter 4 in this volume). These relative yield distributions represent the range of yield responses across farms according to site-specific conditions (see below). In principle, multiple crop and livestock models can be used to characterize uncertainty associated with these models. In addition, the models can be used to evaluate how system adaptations could alter the impacts of climate change. For example, changes in planting dates can be modified in crop models, as can fertilizer application rates and irrigation use. Some models also allow alternative crop rotations to be modeled. However, a number of significant limitations to these models must be recognized. Notably, livestock models are limited in the ways that they can represent the effects of climate on livestock productivity; they are aimed at forage supply and direct effects on animals (mortality, productivity,

and fertility), and interactions between crop and livestock systems are not well represented. Moreover, insect pests, diseases, and weeds are not represented in most models, and the effects of climate on these organisms are not well understood or modeled in their own right.

Economic analysis of impact, vulnerability, and adaptation

A fundamental feature of agricultural systems and households is their heterogeneity: they differ in their various biophysical and socio-economic characteristics. A basic hypothesis that underlies the AgMIP approach is that this heterogeneity is a key factor in how systems are impacted by, and how they can adapt to climate change. This heterogeneity is represented in the economic analysis by using relative yield distributions together with farm survey data, RAPs, and data from global economic models. In the studies carried out by the AgMIP regional teams, the economic model called TOA-MD (discussed in more detail below) is used to simulate the average impacts and the distribution of impacts (vulnerability) of farm households to climate change (Core Questions 1 and 2), as well as the potential adoption of systems adapted to climate change and the economic effects of adaptation (Core Question 3). Sensitivity analysis to model parameters can be used to investigate uncertainty associated with the economic model analysis.

The multi-model approach, uncertainty analysis, and the dimensionality problem

Each of the components of the framework allows for scenario and model uncertainty to be represented. However, there are substantial practical limitations to this approach, because the total number of simulations that must be carried out rapidly increases with each dimension of the analysis. In addition, the number of biophysical and economic models that are currently available and appropriate for a given system is limited by data, model scope, and the research team's capabilities. In the case of economic models, the TOA-MD model is the only economic impact assessment model currently available that is generic, documented, and that can be used consistently across multiple systems and locations (Antle *et al.*, 2010, 2011, 2013, 2014).

A Farm-Household System Approach to Regional Integrated Assessment

The AgMIP approach to RIA is built on the concept of the farm household and the farming system that it uses. This approach is fundamental to a meaningful characterization of vulnerability, as well as meaningful analysis of adaptation, particularly for analysis of farm households in the developing world that often rely on a complex mix of crops, livestock, aquaculture, and non-agricultural activities for

their livelihoods. In contrast, most national or regional studies of climate impacts are based on analysis of individual crop or livestock species, or on aggregated economic outcomes such as crop revenue or net returns. These partial, aggregated measures of impact do not provide an accurate representation of vulnerability. Moreover, aggregate analysis cannot represent important aspects of management that are important to climate adaptation.

Implementation of the AgMIP approach begins with the characterization of existing systems, typically by developing "cartoons" or system diagrams (Fig. 3B; also see Part 2, Chapters 1–10 in this volume). The research team uses this characterization of the current systems to identify the key system components, and the corresponding data and models that will be needed to implement the RIA analysis. In addition, this initial characterization helps to develop RAPs by indicating the kinds of variables that need to be included to project the current system and adapted systems into the future (e.g., global and national prices, see Figure 3A).

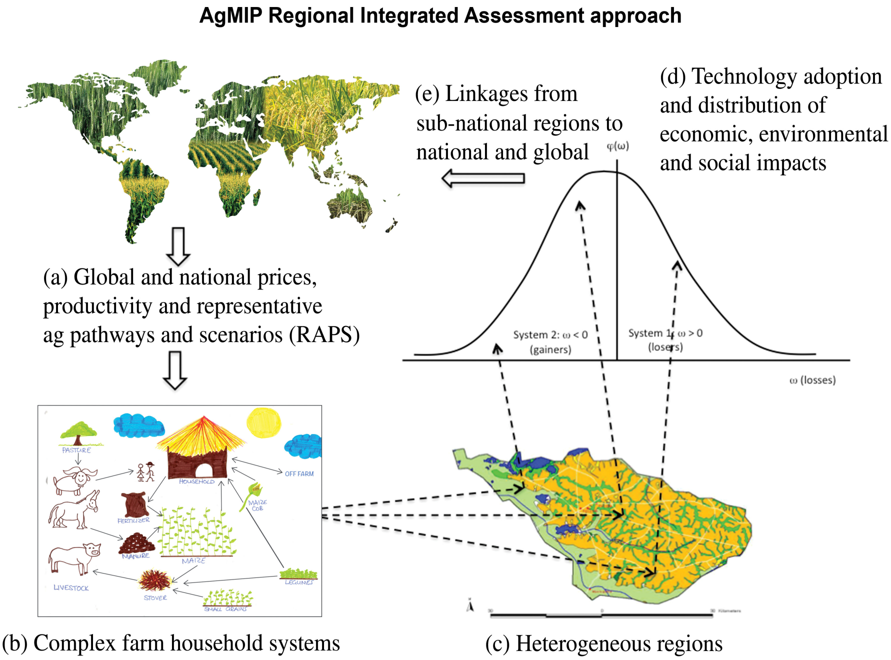

Fig. 3. AgMIP regional integrated assessment approach simulates climate change impact, vulnerability, and adaptation through climate data, biophysical simulation models, and economic models representing a population of heterogeneous farm-household systems. (A) RAPs together with global and national price, productivity, and land-use projections define the biophysical and socio-economic environment in which (B) complex farm-household systems operate in (C) heterogeneous regions. Analysis of technology adoption and (D) impact assessment is implemented in these heterogeneous farm-household populations. This regional analysis may feed back to (E) the country and global scales (farm-household diagram from Part 2, Chapter 5 in this volume).

A key feature of the impact and vulnerability analysis is the representation of biophysical and socio-economic heterogeneity within the farm-household population (Fig. 3C). Acquisition of suitable data to represent all of the main components of the farm-household system is a major challenge in implementing this approach. Typically, farm-household survey data are used to quantify the economic outcomes that are the focus of the impact and vulnerability assessment, as discussed in more detail below and in Part 2, Chapters 1–10 in this volume.

Economic Impact, Vulnerability, and Adaptation Assessment Using the TOA-MD Model

AgMIP uses the Tradeoff Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) to implement the economic analysis component of the regional integrated assessment methodology. The TOA-MD model is a parsimonious, generic model for analysis of technology adoption and impact assessment, and ecosystem services analysis. Antle *et al*. (2010) present a validation of the TOA-MD approach against more complex, spatially explicit models of semi-subsistence agricultural systems. Antle *et al.* (2013) present a validation of the TOA-MD model in an analysis of a major technology adoption and impact assessment study. Further details on the impact assessment aspects of the model are provided in Antle (2011) and Antle *et al*. (2014). The model software and the data used in various studies are available to researchers with documentation and self-guided learning modules at http://tradeoffs.oregonstate.edu. Over 400 researchers globally are now "registered users" of the model, which means that they have completed a basic training course and are using the current version of the model software in a research project.

The chapters in this book by the AgMIP regional teams describe the kinds of farm survey and other data that are used to parameterize the TOA-MD model and its use for climate impact, vulnerability, and adaptation analysis. A complete description of the model and its use can be found in Antle and Valdivia (2014), and at http://tradeoffs.oregonstate.edu.

How does TOA-MD work?

The TOA-MD model simulates technology adoption and impact in a population of heterogeneous farms. Several features of this model are novel as compared to most other economic models that are used for technology adoption and climate impact assessment:

- TOA-MD represents the whole farm production system, which can be composed of (as appropriate) a crop subsystem containing multiple crops, a livestock

subsystem with multiple livestock species, an aquaculture subsystem with multiple species, and the farm household (characterized by the number of family members and the amount of off-farm income).

- TOA-MD is a model of a farm population, not of an individual or "representative" farm. Accordingly, the fundamental parameters of the model are population statistics; means, variances, and correlations of the economic variables in the models and the associated outcome variables of interest. With suitable "matched" biophysical and economic data, these statistical parameters can be estimated for current systems. Using the methods described in the *AgMIP RIA Handbook* (see Part 1, Appendix 1 in this volume), the various elements represented in Fig. 2 can be combined to estimate how the TOA-MD model parameters would change in response to climate change or technological adaptations. These changes in model parameters are the basis for the climate impact, vulnerability, and adaptation analysis.
- TOA-MD simulates impacts that are statistically associated with adoption, using the standard statistical framework for econometric policy evaluation in which economic "agents" — in our context, farms — self-select into "treatment", i.e., choose to adopt or not adopt. The model can be used to estimate the so-called "treatment effects" or the impacts associated with technology adoption. The impacts of climate change estimated by the TOA-MD model are the "treatment effects" of climate change.

As with all models, the TOA-MD model is based on some simplifying assumptions. The key assumptions are:

- In making technology choices, farm decision-makers are assumed to be economically rational. In the version of the model being used by the AgMIP regional teams, technology choice and climate impacts are based on expected economic returns. The simulation model uses data on the spatial variability in observed crop and livestock yields and other variables (production costs, farm size, household size) to represent heterogeneity in the farm population.
- Economic returns in the farm population are assumed to follow a normal (Gaussian) distribution at the lowest level of disaggregation in the analysis (i.e., what are called the "strata" in the TOA-MD model). Thus, an appropriate stratification of the population can play an important role in the analysis. When data are aggregated across strata, the resulting distributions are mixtures of normal distributions and are thus non-normal, as is typically the case in actual data.

Using the TOA-MD model for climate impact assessment

In the TOA-MD model, farmers are presented with a simple binary choice: they can operate with a current or base production System 1, or they can switch to an

alternative System 2. In a technology adoption and impact analysis, the model simulates the proportion of farms that would adopt the new or alternative system, as well as the impacts of the new system by simulating impact indicators defined by the user.

The model is used to assess climate impacts by using a simple analogy to technology adoption. Farmers cannot choose whether to have climate change or not, but if farmers had such a choice, those that would choose to "adopt" climate change are those who would gain from it; farmers that would prefer not to "adopt" climate change are those who would lose from it. An important implication of this model, when used to predict a technology adoption rate, is that the rate is typically between 0% and 100%; it is rare for all farms to adopt a technology because in a heterogeneous population not all farms perceive it to be beneficial. The analogy to climate impact assessment is that there are typically both losers and gainers from climate change. The phenomenon of losers and gainers from climate change can be explained (at least in part) by the heterogeneity in the conditions in which the farms operate, such as soils, water resources, topography, climate, the farm household's socio-economic characteristics, and the broader economic, institutional, and policy setting (see Fig. 3).

In a climate change analysis, it is necessary to distinguish among three basic factors that affect the expected value of a production system: the production methods used, referred to here as the *technology*, the physical environment in which the system is operated, i.e., the *climate*, and the economic and social environment in which the system is operated, i.e., the *socio-economic setting* that we shall refer to as a representative agricultural pathway, or RAP. RAPs are qualitative storylines that can be translated into model parameters such as farm and household size, prices and costs of production, and policy, as discussed in Part1, Chapter 5 in this volume. RAPs represent agricultural development, independent of climate change. Following the three core climate impact assessment questions discussed above, the model can be set up with appropriate combinations of parameters to represent the corresponding technologies, climates, and socio-economic conditions (see Table 1).

Economic foundations of the TOA-MD model

The core of the TOA-MD model is a "threshold" model of technology adoption. A farmer using a production system h (defined as a combination of technology, climate, and RAP) earns returns each period equal to $v_t = v(h)$. Over T time periods, system h provides a discounted net return (V_t) of

$$V(h) = \sum_{t=1}^{T} \delta_t v(h), \tag{1}$$

where δ_t is the relevant time discount factor.

Table 1. Overview of climate, crop model, and economic model components needed in simulation sets required to compare production-system states and answer Core Questions 1, 2, and 3. Note that three crop model cases are defined, and for this table the future period is assumed to be the RCP8.5 mid-century (2040–2069).

Core Questions	Simulation Sets	
1. What is the sensitivity of current agricultural production systems to climate change?	Current **Current Climate** **Current Production System** 1980-2009 Climate Crop/Livestock Simulations no Adaptation (#1) TOA without RAP	Climate Change Sensitivity **Future Climate** **Current Production System** 2040-2069 Climate Crop/Livestock Simulations, no Adaptation (#2) TOA without RAP
	Economic Simulation #1 →	

Core Questions	Simulation Sets	
2. What is the impact of climate change on future agricultural production systems?	Future without Climate Change **Current Climate** **Current Production System with Trend** 1980-2009 Climate Crop/Livestock Simulations, (no adaptation, with RAP) TOA with RAP 1	Future with Climate Change **Future Climate** **Current Production System with Trend** 2040-2069 Climate Crop/Livestock Simulations, (no adaptation, with RAP) TOA with RAP 1
	Economic Simulation #2 →	

Core Questions	Simulation Sets	
3. What are the benefits of climate change adaptations?	Future Climate Change without Adaptation **Future Climate** **Current Production System with Trend** 2040-2069 Climate Crop/Livestock Simulations, no Adaptation (same as #2) TOA with RAP 1	Future Climate Change with Adaptation **Future Climate** **Climate-adapted Production System with Trend** 2040-2069 Climate Crop/Livestock Simulations with Adaptations (#3) TOA with RAP 1 and Adaptations
	Economic Simulation #3 →	

When the production system changes, because of a change in technology or climate or both, expected returns at each site also change. The effect on a farm's returns of changing from one system (call it System 1) to another (call it System 2) is $\omega = V(2) - V(1)$. Thus, if ω is positive it represents the loss, or opportunity cost, associated with switching from System 1 to System 2, and if negative it represents a gain. If we define the density $\phi(\omega)$ as the spatial distribution of gains or losses in the population of farms, the percentage of farms with $\omega < a$ (with a an amount in, e.g., dollars per hectare) is

$$r(a) = 100 \int_{-\infty}^{a} \varphi(\omega) d\omega. \tag{2}$$

In the standard technology adoption analysis, farmers may be able to choose to continue using System 1, which embodies one type of technology (say, the base technology defined above), or to switch to System 2, which embodies a different technology (say, a technology adapted to a different climate). In this case of voluntary technology adoption, note that a farm will switch if $\omega = V(1) - V(2) < a$, which implies that $V(1) < V(2) + a$. Thus $r(a)$ can be interpreted as the proportion of adopters of System 2 that experiences a gain or loss ω from switching, and which are also given a payment (if positive) or made to pay a penalty or tax (if negative) of a dollars per hectare to switch. A farmer with $\omega < 0$ will switch from System 1 to 2 without a positive incentive payment, and $r(0)$ is interpreted as the adoption rate that would occur without an incentive payment or penalty. The model is general and can incorporate a number of different kinds of policy interventions. For example, if a government or other entity wants to encourage additional adoption, a positive incentive can be offered to adopters, in which case the adoption rate is $r(a) > r(0)$ for $a > 0$. Conversely, to discourage adoption, a negative incentive (i.e., a penalty or tax) can be imposed on adopters (say, a tax on the decrease in environmental services associated with the use of System 2).

Climate Impact and Vulnerability Assessment: Answering Core Questions 1 and 2

In a climate impact and vulnerability assessment, ω is interpreted as the loss from climate change, and those farm households that are adversely impacted (i.e., have $\omega > 0$) are defined as vulnerable to climate change. Consider the situation in which farmers are using a particular production system, defined now as System 1. If no adaptation is possible, their only option is to use the same system when the climate changes (call this System 2). In this type of analysis, Equation (2) can be interpreted as showing the proportion of farms with losses less than a, i.e., with $\omega < a$. Thus, $r(0)$ is interpreted as the proportion of farms that are positively impacted, and $1 - r(0)$ is

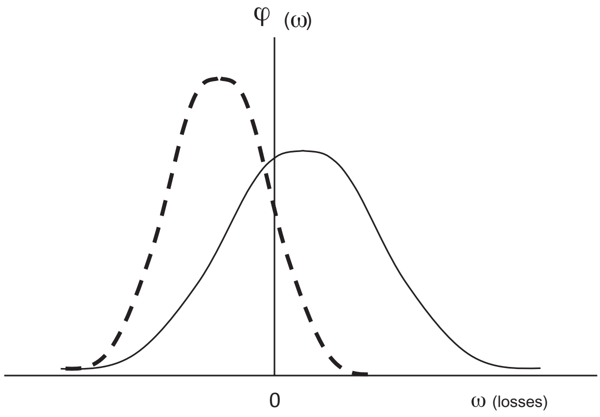

Fig. 4. Vulnerability assessment using the distribution of losses associated with climate change. The area under the distribution on the positive side of zero is the proportion of losers and a measure of vulnerability. Here the solid distribution represents a system for which the average loss is positive and there are more losers than gainers. The dashed distribution represents a system with more gainers than losers. The goal of climate adaptation is to shift the distribution leftward.

interpreted as the proportion of farms that is negatively impacted, and this proportion can be interpreted as a measure of vulnerability to climate change. For Core Question 1, this type of analysis is done under current conditions; for Core Question 2, it is done in combination with RAPs to project the system into the future (Fig. 1 and Table 1).

Figure 4 shows the distribution of losses and illustrates the analysis for two cases. Note that the area under the distribution on the positive side of zero is the proportion of losers and a measure of vulnerability. The solid distribution in Fig. 4 represents a system for which the average change in income is negative and there are more losers than gainers. Note, however, that even in this case there are some gainers, i.e., some individuals in the population for $\omega < 0$. The dashed distribution represents a system that is less vulnerable to climate change, and has more gainers than losers. In this case, even though gainers outnumber losers, there are still some losers with $\omega > 0$. It is also important to note that both the mean and the dispersion of the distribution of gains and losses matters to the measurement of vulnerability. Indeed, the dispersion (i.e., variance) of the distribution of opportunity cost represents the heterogeneity of the impacts of climate change on the population. In the AgMIP RIA methodology, this heterogeneous response to climate change derives from the productivity impacts of climate change incorporated in the model through crop and livestock simulation models (see discussion below), as well as the socio-economic heterogeneity in the farm-household system due to variations in farm size, household size, and non-farm income.

In addition to the proportion of vulnerable farm households, the TOA-MD model can simulate the magnitude of impacts on the adopters (or gainers), the non-adopters (or losers), and the aggregate effect for the entire population. The model calculates impacts on farm net returns, and *per capita* household income, and can also compute income-based poverty rates for the gainers, losers and the overall population. Other outcomes, such as nutritional impacts, can be simulated if suitable data are available (see Antle (2011) and Antle *et al*. (2013) for examples).

Climate Adaptation Analysis: Answering Core Question 3

When farmers are confronted with an environmental change such as climate change, they may choose a different technology that performs better in the new environment, if one is available. Thus, call System 1 the "old" system used with the changed climate, and call System 2 the adapted system used with the new climate, as in Core Question 3 defined above (also see Fig. 1). The TOA-MD model is used in an adaptation analysis to determine the proportion of farms that would adopt this "adapted" system under the changed climate, following the description of an adoption analysis presented above. Using the logic of this model, it follows that with adaptation the proportion of "losers" from climate change would decrease and the proportion of "gainers" would increase. Referring again to Fig. 4, the effect of an adaptation is to shift the distribution of gains and losses leftward, such as the shift from the solid distribution to the dashed distribution. Note that how the adaptation affects both the average loss, as well as the dispersion of losses, will affect the benefits of the adaptation.

Incorporating crop and livestock simulations into the TOA-MD analysis

The analysis of climate impacts, vulnerability, and adaptation depends critically on how the effects of climate change are estimated and incorporated into the economic analysis. The various economic studies in the literature do this in a variety of ways. Some studies directly incorporate climate variables into statistical models that represent average yield, economic returns, land values, or other economic outcomes for some unit of analysis. Most such studies use data averaged over some spatial unit. This type of model can be used to estimate parameters of Systems 1 and 2 in the TOA-MD model, by using them with future climate projections to estimate changes in the economic returns to a production system. However, there are some obvious disadvantages of using these statistical models, most notably the fact that their parameters are based on historical data that embody the historical technological, policy, and social and other conditions in which the farmers represented in the data were operating. Thus, such studies effectively quantify the impacts of projected

future climate on the systems that were observed under past historical conditions. Clearly, when one considers how rapidly technological, social, policy, and other relevant conditions change, the incentives for farmers to adapt to new climate conditions, and the long-term horizons over which climate changes occur, this type of approach is at risk of presenting a substantially biased picture of the impacts of climate change under what are likely to be very different future conditions from past historical experience.

A major goal of the AgMIP methodology is to break out of this "historical" climate impact assessment model. One key element in the analysis is to use process-based crop and livestock simulation models to simulate impacts of climate change on the productivity of the systems in use as well as in adapted systems. As explained in detail in Appendix 1, the *AgMIP Regional Integrated Assessment Handbook* (also see Table 1), the method used for this analysis is to simulate yields under current climate and under future climate, and then to define the *relative yield* as the ratio of the future average yield to the current average yield. These relative yields are simulated for a representative sample of sites in a region, and these data are then used to estimate the *relative yield distribution* in the population. This relative yield distribution is then used to calculate the parameters of the TOA-MD model that shows how climate change may impact the distribution of economic outcomes in the farm population.

Using RAPs and Global Economic Models to Incorporate Future Socio-economic Conditions into the TOA-MD Analysis

As indicated in Figs. 1 and 2 and Table 1, the analysis of Core Questions 2 and 3 are carried out under plausible future conditions defined by RAPs. To project the average level of productivity into the future that would occur with ongoing technological advancements (not associated with climate change or adaptation), the AgMIP methodology utilizes the technology trend projections developed for global economic models (see von Lampe *et al.*, 2014), together with the assessment of technology trends made by research teams in the development of RAPs (see Chapter 5). Likewise, the AgMIP methodology incorporates the price projections from global economic models into the development of regional RAPs.

Conclusions

The AgMIP regional integrated assessment methodology incorporates a number of major advances in the way that climate impact, vulnerability, and adaptation are being modeled. At its core is a protocol approach that should result in impact

assessments being more scientifically credible and thus ultimately having greater value to the various stakeholders. Moreover, the use of the protocol approach should enable closer scrutiny and intercomparison of models and methods so that they can be improved over time. There is also the hope that by creating a truly transdisciplinary, systems-based approach, impact assessments and evaluation of adaptations will be more meaningful to stakeholders. Over time, there is great potential to improve the models and data so that it will be possible to incorporate more important features of current and possible future systems, including multiple crops, inter-crops, livestock, and non-agricultural (e.g., crop insurance) sources of income. It should also be possible with additional research investment to improve the assessment of the key uncertainties in crop, biophysical, and economic dimensions of assessments. The chapters in this volume (Part 2, Chapters 7–10) demonstrating the use of this approach represent a first step towards the eventual full realization of these new methods and their application.

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